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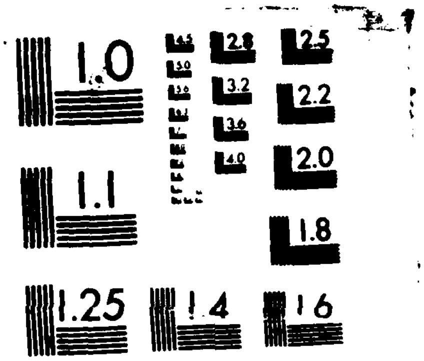

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Microstructures technology is the key component of the microelectronics revolution, which is causing profound and rapid changes in information processing, computation, robotics, communication, manufacturing, national security, and international trade. The current leadership of the United

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States is being vigorously challenged by other countries. To maintain a leadership position, or even a competitive position, adequate funding of near-term and long-term research at universities and non-profit laboratories is essential, along with improved transfer of results from the research laboratory to commercial products. We recommend enhanced and well-targeted funding of microstructures technology and research.

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LEADERSHIP IN MICROSTRUCTURES TECHNOLOGY

FINAL TECHNICAL REPORT

A REPORT OF THE STEERING COMMITTEE
FOR THE
WORKSHOP ON THE FUTURE OF MICROSTRUCTURES TECHNOLOGY
SEABROOK ISLAND, SOUTH CAROLINA
OCTOBER 13-15, 1985

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March 3, 1986

LEADERSHIP IN MICROSTRUCTURES TECHNOLOGY*

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TABLE OF CONTENTS

SUMMARY

Microstructures technology is the key component of the microelectronics revolution, which is causing profound and rapid changes in information processing, computation, robotics, communication, manufacturing, national security, and international trade. The current leadership of the United States is being vigorously challenged by other countries. To maintain a leadership position, or even a competitive position, adequate funding of near-term and long-term research at universities and non-profit laboratories is essential, along with improved transfer of results from the research laboratory to commercial products. We recommend enhanced and well-targeted funding of microstructures technology and research.

I. INTRODUCTION

We are in the midst of a technological revolution, currently led by the United States, which many believe is more significant than the industrial revolution of the 19th century. This revolution, which has been variously called the microelectronics revolution, the computer revolution, the microchip revolution or the information revolution, could also be called the microstructures revolution since the science and engineering of artificial microstructures is the key component of the revolution. Future generations will likely refer to our era not as the nuclear age or the space age, but by some term that reflects the profound impact of artificial microstructures on economies, national security, the quality of everyday life, the transformation of industrial society, and communication among peoples of the world. This field, and perhaps also bioengineering, are where the action is! Some of the best scientific talent in the world is pursuing a broad spectrum of research,

engineering, education, application, product development, manufacturing and commercialization based on artificial microstructures. At present, the USA is fortunate to have a major percentage of that talent in its industries, universities, and non-profit laboratories. However, this percentage is changing rather quickly. Funding policy at the Federal level, especially in agencies such as the NSF which are committed to promoting the long-term health of science and engineering, is pivotal to sustaining the current leadership of the USA. Other nations and groups of nations recognize the nature of the revolution and seek leadership for economic vitality, military security and as a matter of national pride.

In 1978, at Airlie House in Virginia, a workshop was held to discuss the impact of microstructures science and engineering and recommend funding policy. The workshop produced an NRC report that had a beneficial impact on the field and helped to attract additional talent. However, recommendations with regard to funding were, for the most part, not implemented.

A second workshop was held in October, 1985 at Seabrook Island, South Carolina. This report is a brief statement, based on that workshop, prepared by the Workshop Steering Committee. It does not address the technical content of the Workshop presentations but instead seeks to abstract the significance of microstructure science and engineering, and to recommend a course of action for funding agencies such as the NSF.

II. IMPORTANCE OF MICROSTRUCTURES TECHNOLOGY

In the human body, protein molecules, with dimensions of the order of a nanometer, are embedded in the membranes of cells and organelles, where they perform enzymatic and other basic operations analogous to switching. In

modern electronics, the switching function is performed by transistors with dimensions more than 1000 times larger. The motion, judgement, communication and other spectacular functions we observe in humans are the product of a complex assemblage of elemental microstructures such as the embedded proteins. Information on how to assemble a human is stored in DNA macromolecules. The high density of data storage in DNA and the enviable capabilities of the human mind and body far exceed what we can do today with artificial microstructures. This is not to imply that manmade systems should try to emulate biological systems. Quite the contrary! Manmade systems bypass obvious problems of biological systems: slow speed, environmental restrictions, aging and disease, to name a few. The biological example is useful primarily in that it provides clear signposts that the development of manmade systems for computation, judgement, manufacturing or performing other complex tasks has a long and exciting road ahead. The way is not clear, but it is clear that there is much yet to be discovered, and this provides an enormous opportunity for creative research, both by individuals and groups of investigators.

Considering first computation systems, we can see a clear need and market for computer systems that can learn by experience, manipulate and process symbols, understand images and spoken language, perform design synthesis, and carry out intelligent data-base management. In short, systems that perform some of the functions of the brain but faster and better will surely come. The only question is <u>where</u> they will be manufactured. In the field of communications, optoelectronics has a clear potential for continuing the shrinkage of barriers and costs. The sensing of chemicals and physical variables (pressure, flow, acceleration, etc.) and the integration of such microsensors with electronics and microactuators has already begun to change

our automobiles, and will surely change a broad spectrum of traditional industries. Inventions here could have profound, totally unanticipated effects. Suppose, for example, that future inventions could carry out sensing and control of biochemical reactions on a microscopic scale, or extract precious metals from seawater. Such a scenario is no more unbelievable than the microprocessor chip or recombinant DNA would have appeared 40 years ago.

In short, artificial microstructures have a central and obvious role in present and future computation, communication, sensing, robotic and manufacturing systems. The future may well see a merging of solid state microstructures and macromolecular technology. In all probability, presently unforeseen inventions will have a profound impact on society and industry. It is important that the USA hold a leadership position.

III. CURRENT STATUS OF MICROSTRUCTURES TECHNOLOGY

The preponderence of research on artificial microstructures is focused at present on solid state electronic devices. Substrates are generally single-crystal semiconductors of high quality. In some cases, epitaxial layers are used and near atomic-level control in the vertical dimension is exercised in forming the layers. Lateral dimensions of minimum features range from around one micrometer for commercial devices to below 0.1 μm for certain experimental devices in the research laboratory. Commercially manufactured memory chips contain as many as 10^6 transistors, and this number will very likely double and quadruple in the next few years.

Many experts feel that Si integrated circuit (IC) technology in its present form will be extended down to minimum feature sizes of 0.5 or perhaps

0.25 μm, but beyond that new approaches will be required in order to continue the well-known trends of dimensional shrinkage and increasing number of devices per chip. Some have predicted that quantum-effect devices, with dimensions of the order of 500 Å, fabricated in III-V compound semiconductor materials, will supplant the transistor. Such devices will not be individually interconnected with wiring, but instead some kind of near-neighbor coupling will be required. Assuming this scenario, it is obvious that a great deal of research needs to be done on the fundamentals of electron transport, and that new inventions will be required to achieve large scale systems based on quantum effects. Moreover, materials and fabrication technologies face formidable challenges in developing means to manufacture precision artificial microstructures with minimum feature sizes of the order of 500 Å. There is no clear route. However, here again it is important that the USA hold a leadership position. Fortunately, there is no shortage of creative ideas and energetic individuals in the university, government and industrial laboratories; only a shortage of funds to support their proposed research.

In the microsensor and micromechanical areas there are many creative individuals eager to pursue novel research. The new ideas and inventions that are needed in these fields will come if they are allowed to pursue that research.

IV. IMPORTANT AREAS OF RESEARCH

The following list is meant to provide a sampling of areas of research in artificial microstructures that deserve adequate, long-term support because of the probability of future payoff. Obviously, such a list cannot be all-inclusive.

It reflects, of course, the views of those who have created it. Unanticipated developments will almost certainly change our perceptions in the future.

A. Materials

Materials have always been, and will likely continue to be, the pacing element in systems based on microstructures. Continued research, especially on thin films, interfaces, and artificially-structured materials is essential. (The latter topic was the subject of a recent NRC report, "Report on Artificially Structured Materials", National Academy Press, Washington, DC, 1985.) Approaches that circumvent existing materials constraints, and that eliminate or control random crystallographic defects should be emphasized.

Crystalline materials will likely continue to play the central role in systems based on artificial microstructures. However, better understanding of amorphous materials, both inorganic and organic, is also necessary. Efforts to combine the unique properties of macromolecules with inorganic microstructures should be encouraged. However, it is important that this field proceed beyond mere speculation and generalities to good science and engineering.

B. Transport Phenomena and Device Technology

Transport is fundamental to systems based on microstructures. Recent investigations into electron transport in 1-D and 2-D electron gases, and in disordered small microstructures, has revealed a plethora of exciting quantum phenomena. For example, the 1985 Nobel Prize in physics was awarded for discovery of the quantum Hall effect. Research

may provide the groundwork for highly complex computation systems based on quantum-effects. Research on optical, elastic and soliton transport should also provide benefits. How to utilize transport phenomena to accomplish a function is the domain of device technology. Here again, recent years have seen a burgeoning of novel configurations (e.g., high-electron-mobility transistors). Since the devices that will supplant the transistor are as yet undeveloped, research in this field is essential. In current systems each transistor is individually wired. Past experience has shown that as integrated circuits become more complex the fraction of area occupied by wiring diverges, and delays become a limiting factor. Hence, new ideas to circumvent the wiring crisis are crucially important.

C. Submicron and Sub-1000 Å Fabrication Technology.

Two-dimensional (2-D) patterning is central to the fabrication of devices and integrated circuits. In nearly all cases patterning is done with the planar process: lithography followed by etching, growth, doping or deposition. The technology for 2-D patterning must be capable not only of making fine features but also of placing features within a 2-D field accurately and with precision. The 2-D field should contain a large number of pixels, 10^6 to 10^{12}. Several 2-D fields are frequently superimposed (i.e., aligned) on top of one another at different stages of a fabrication sequence. The cross-sectional geometry of fabricated features is just as important as the 2-D geometry. Patterning must be reliable, high yield (i.e., low defect density) and low cost (i.e. high throughput).

Research is required in nearly all areas of fabrication technology. For example, although electron-beam lithography is capable of writing features as small as 1 nm, it is too slow and costly in present conceptions to be used in manufacturing. There is no clear successor to UV optics for high throughput lithography at linewidths below 0.5 µm. New ideas are required as well as continued development of UV, x-ray and ion methods. Alignment, etching, resists, inspection, deposition, and yield enhancement are all areas in which research is needed.

D. Systems

Means of performing computation that go beyond current methods should be actively promoted. (Certainly, the brain does not work like a contemporary digital computer.) Recently, neural networks were proposed for dealing with problems that require a good answer but not necessarily the absolute best. This idea is being pursued actively at several locations. If a new generation of devices beyond the transistor emerges it will almost certainly require a concommitant change in system architecture and computation methods.

V. RECOMMENDED COURSE OF ACTION

To maintain the technological leadership of the USA in the many areas included within the field of artificial microstructures will require innovation on the part of creative individuals, collaboration within groups of talented individuals, effective training of the next generation of scientists and engineers, and effective transfer of scientific knowledge into competitive products. All of these require the right environment of physical facilities

and funding. At present there is no shortage of energy, enthusiasm, or creativity on the part of the scientists, engineers and students in the field. The <u>only issues are facilities and funding</u>. For these reasons we make the following recommendations.

A. Individual Investigators

Many of the innovations of the past have come from creative individuals in the right place at the right time. There is every reason to believe individual investigators will be able to do this in the future. For support of individual investigators the existing system of proposal submission and peer review works well, although it should work more quickly and in some cases more generously. It is extremely important that existing programs to support individual investigators not be diminished. Minimization of paperwork is desirable.

B. Groups of Individuals

Groups of individuals should be able to submit proposals for long-term support of joint efforts. In the past, many such efforts funded by the DOD, have been productive. The National Submicron Facility has been effective in providing a much-needed national resource for advanced microstructures technology. The current trend of funding large Engineering Research Centers may do much to help graduate education in those schools that receive such centers. However, progress in the field of microstructures technology requires support for all groups that have

the potential to make near-term and long-term contributions. Lack of equipment and facilities, which have become extremely expensive in recent years, is a major problem for university research.

C. Education and Training

In those universities that do not have strong research capabilities it is important to maintain an environment that will attract effective teachers. Summer positions for faculty in industry, and regional cooperatives may help. In the research universities, education and training are effective at the present time.

D. Transfer to Industrial Practice

We should build into the university research environment some incentive to go beyond the publication of a research paper. At present, university faculties and students have few means and little incentive to see their results implemented in industry. Financial incentives may be effective. An attempt to accelerate the transfer has been made by the Semiconductor Research Corporation (SRC) in structuring their research support. This first effort needs considerable refinement and expansion.

E. Leadership

Because of its pervasive impact on the nation's economy and security we believe the case for enhanced support of microstructures technology and research is very strong. In this field, which is so exciting and rapidly moving, the best talents are reluctant to spend inordinate time in the pursuit of funding. (In contrast, many slow-moving, low-impact

fields have no shortage of skilled lobbyists for continuation of the status quo.) This exacerbates the problem of effectively distributing limited funds. Medium to long-term support for demonstrated high quality research is desirable. One suggestion we would have is to rotate bright young investigators, for short periods, onto the highest decision making bodies, such as the NSF Science Board. This would inject some inexperience, but also insight from the grass roots, fresh ideas and stimulation, and tend to lessen disproportionate support of low payoff fields. The importance of the microstructures field and the need for appropriate support should be effectively communicated to Congress and the executive branch.

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